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BOOK REVIEWS

Koyna Earthquake of December 11, 1967: Report of the Expert Committee on Electrical and Mechanical Equipment. UNESCO, No. 1489/BMS.RD/SCE, Paris, September, 1969, 52 pp.

Hydroelectric power generators are common in seismic regions throughout the world and their ability to withstand earthquakes is important to public welfare. There is very little information in the literature about the effects of earthquakes on such installations; hence, the report of the Expert Committee should be of special interest to all who are responsible for designing and operating hydroelectric plants. The report describes what happened at the power station during and after the earthquake and makes recommendations for improving the earthquake resistance. The magnitude 6.5 earthquake, thought to have been triggered by the reservoir loading, centered about 3 km south of the dam. A strong-motion accelerometer installed within the 338-ft high, concrete gravity dam recorded a peak acceleration of about 50 per cent g, with the frequencies in the motion being appreciably higher than those shown by U. S. earthquakes. The 540-MW electric-generating station was located about 8 km WNW of the dam. The effect of the earthquake on the dam has been described in a paper by G. V. Berg *et al.*, The Koyna, India Earthquakes, *Proceedings of the Fifth World Conference on Earthquake Engineering*, Santiago, Chile, 1969, and also in UNESCO *Report of the Committee of Experts on Koyna Earthquake of December 11, 1967*, New Delhi, 1968. The effect of the earthquake on the power generating station is summarized in the following description which has been abstracted from the report.

Observations Made during and Immediately after the Earthquake

At 04.20 hours on December 11 1967 a severe earthquake of very high intensity caused failure of power supply. On observing the severity of the earthquake and the tripping of the units, the shift engineer on duty opened out the breakers on Bombay lines 1 and 2 and after a few seconds, the Karad line breaker also. On failure of the ac auxiliary supply, he tried to start the house generator. The house generator was started by governor-floor operators and the ac supply resumed. In the meantime, operators at the governor floor were instructed to stop the units and quit the powerhouse premises. Governor-floor operators on stages I and II side, while shutting down the units, applied brake jets on all of the units, except unit 2 where they kept the air brakes "ON" at full speed. After starting the house generator, they left the powerhouse. Stage II governor-floor operators, on receiving instructions from the shift engineer and confirming that the ac supply was "ON" initiated stopping operations of the units. They used brake jets for units 5, 6 and 8 at about 300 rpm and brakes at 75 rpm; the brake jet could not be used on unit 7, so this was stopped by applying brakes from full speed. After the stopping operations were completed, they received a call to leave the powerhouse. By this time all of the staff had left the powerhouse.

The first group of maintenance personnel entered the powerhouse at 08.30 hours on December 11 1967. On the hydraulic equipment, all of the spherical valves were closed, all of the by-pass valves were closed and all of the bypass gate valves were open. Opening limiters on units 1 to 4 were 50 to 80 per cent open. Opening limiters on units 5 to 7 were 0 per cent open. Butterfly valves 1 to 4 were open. Air brake valves on units 1 to 4 were open.

On the electrical side, all of the field breakers and 220-kv breakers were in "OFF" position, except the 220-kv breaker of unit 4 and Bombay line 2. Cable end isolators of units 5 to 8 and 220-kv main bus isolators were open. Bombay line 1 and 2 main bus side isolators were open. All other isolators were in normal service position. Compressed air pressure was 0 kg/cm^2 on the 30 kg/cm^2 system. Bombay line 2 and unit 4 breaker positions were "ON" and air pressure was 0 kg/cm^2. All other breakers and tank pressures were between 15 and 15.4 kg/cm^2. Compressors were not running, because the main 415-Vac incoming breaker was tripped. The ac supply to carrier cubicles, air-conditioning plant and lighting was dead, for the same reason. The converter was running and carrier cubicles were in service, fed by the emergency ac supply.

The unit boards and the control board indicated that units 1 through 7 had tripped, that there had been excessive overspeed, that pressure oil vessel was low and that pressure container oil level was low. The frequency recorder chart indicated that the system frequency, which was 49.8 cps before the start of the occurrence, varied from below 48 up to 52 cps and beyond.

In butterfly valve 1, the grease on the servomotor shaft was wiped out, but the valve position was open. Tripping could have occurred as a result of shock leakage on the bypass filling in the pressure shaft, so that, on closing, the air valve automatically opened the butterfly valve.

Stopping operations for the transformer cooling panels and switchyard isolators were carried out afterwards by the maintenance staff.

All main cooling water pipeline valves were open. Closing operations were carried out by maintenance and operation staff on December 13 1967.

Damage to Plant and Equipment in the Powerhouse

220-Kv C. T. 200/1/1 R ph. for bus coupler bushing had hairline crack and oil was leaking.

33-kv P. T. of 10-MVA transformer was found leaking through gasket.

Bombay line 2, ABCB phase, "R" hollow column insulator sheared near the joint between first and second column.

Unit 4, 220-kv ABCB phase, "Y" hollow column insulator had crack at similar place as Bombay line 2 but in bottom column.

220-kv isolator clamps were loose.

Bombay line 1, bus side C. T. phase, "Y" and ABCB structure level disturbed.

Unit 5, 6000-amp switch phase "B," one support insulator cracked.

Control circuit: some of the connections found loose. One interlock circuit connection came out of terminal.

Some fluorescent lighting tube fixtures fell down near unit 8 governor floor.

Relay Room building: one lead acid battery cell found slipped.

10-MVA transformer moved by $1\frac{1}{4}$ to $1\frac{1}{2}$ in.

Mechanical.

South side intake (HRT) gate servomotor foundation bolts and nuts came out of their seats. Mercury vapor lamps damaged, lightning arrester on the tower found sheared.

Lower and upper guide-bearing adjusting disc pieces of the holding pins of individual pads strained and almost all had hairline cracks.

Shaft and bearing alignments disturbed.

Auxiliary generator commutator on units 2 and 3 scratched due to the bending and twisting of brush holders.

Dome lights shattered on units 1 to 4.

Air-conditioning plant.

Shaft alignment disturbed in both units.

Starter contacts and switch contacts of ventilation blower shattered and fell.

Resumption of Operations

Unit 1 was put back on the line at 21 hr, December 13, and unit 3 was on the line the following day. Unit 4 was on the line the 16th, unit 8 on the 19th, unit 2 on the 23rd, unit 5 on the 28th, unit 7 on the 29th and unit 6 on the 30th.

Observations on Damage and Repair

Immediately after the earthquake, a preliminary examination revealed that the hydraulic system as a whole had not suffered any noticeable damage and it was therefore decided to check the alignments of the different machines. First, the house generator was started. No appreciable change having been found in the alignment of machine 1, it was started on no-load and kept running to watch for any undue temperature rise. After a few hours run without any undue occurrence, this machine was taken on load. Subsequently, the other machines were checked one by one and tried out.

All eight generators had tripped as a result of operations of relays. Their temperature and pilycomp records indicated a possibility of damage to the thrust bearings of machines 3 and 4. Subsequent examination of these showed, however, that they were in perfect condition.

Examination of the guide bearing adjustments of the four units of stage I revealed that the adjustment discs had been dented and deformed, even though the guide bearings themselves were not damaged. For the immediate postearthquake maintenance, these were replaced in all the units by adjustment discs of similar specifications made from material procured locally. The commutator of the auxiliary generators of units 2 and 3 were seen to have been damaged because of the rocker arm and the bending and twisting of brush holders. Their commutators had to be resurfaced. The bearing bridge level of unit 1 was found in order. Units 2 and 4 had to be realigned. Realignment was not felt necessary for unit 3. Their temperature rise after the runs was found to be within limits.

The temperatures recorded on the stage II units were within the limits even after the occurrence of the earthquake. With a view to bringing unit 7 on line, it was started without realignment of the shaft. However, since the temperature had a rising tendency, the unit was stopped and the shaft realigned. The babbit lining of the generator, the upper and lower guide bearings and the turbine guide bearings were found to be in good condition. In general, the following maintenance works were carried out on stage II units:

Unit 8—the upper guide bearing bracket was shifted and the shaft realigned.

Unit 7—the upper bearing bridge lower guide bearing brackets were shifted and the shaft realigned.

Units 6 and 5—the upper bearing bracket was leveled with shims and shifted. The shafts were in central position, and hence, no detailed alignment of the shaft was deemed to be necessary.

All eight turbine generators in the generating station had tripped by operation of the governor. The spherical valves had closed. All of the machines were stopped by the emergency-stopping procedure upon occurrence of the earthquake, except unit 2 which was stopped by normal procedure. Unit 7 was, however, stopped with full air brakes on, because of difficulty experienced with the brake jet due to auxiliary power failure.

It was observed that the dome lights of stage I units were shattered. The temperature records after the stoppage of the units on occurrence of the earthquake were satisfactory. The indication of low pressure and low oil level in the governor container for stage I units had picked up. This may have been due to the air pressure for the governor oil container having been somewhat lowered even before the earthquake.

All the butterfly valves were open. However, butterfly valve 1 appeared to have closed and opened again, for reasons which cannot be elucidated. In general, all the equipment in the emergency valve house was in normal condition.

Immediately on the occurrence of the earthquake, both the Bombay lines and the Karad line breakers had been tripped manually. All of the machines appeared to have tripped because of operation of relays and the machines were all in de-excited position. However, the sequence of tripping of the breakers is not known clearly, except in the case of the line breakers operated manually.

After the operation of the breakers the 220-kv isolators of the stage II yard were opened out from the control room. The isolators of the stage I yard were opened manually an hour after the earthquake, the entire operation taking about $\frac{1}{2}$ hr. During the opening of these switches, it was noticed that all of the three phases of the breakers on Bombay line 2 and generator 4 were in closed position as a result of underpressure of air. The isolating switches of stage I, including the switches for line 2 and generator 4 were opened manually, since by this time the feed from Kandalgaon had been isolated manually from that end.

Because of the tripping of stage I units, the auxiliary supply to the units had failed. The feeder to the compressor stations of the 220-kv circuit-breaker compressors had tripped. A possible explanation is that, on the resumption of supply, two or more compressors may have tried to start simultaneously for which the setting of the relay may not have been adequate. The relays have since been set for 800 amps instead of 200 amps, in order to cover this contingency.

It is understood from Messr. Tata's engineers that, after the earthquake, it was found that in Tata's system one transformer had tripped as a result of zero sequence voltage, and another transformer was tripped by Buchholz relay. Also a negative sequence alarm was given.

There was an automatic closing of the 220-kv ABCB of unit 4, due to failure of compressed air. On the occurrence of the earthquake, the contingency of the breaker connecting the unit back to the system did not arise; the damage that would have been caused to these units, had this occurred, would have been enormous.

The Neyrpic overspeed relays for stage I turbines are of the hand-reset type. It may thus be concluded that the unit had tripped as a result of picking up of overspeed relays. The stage II Charmilles overspeed relay, incorporating mercury contacts was of the self-reset type. In consequence, it cannot definitely be said whether the relay as a whole had initiated the tripping or whether the mercury contact alone had tripped the stage II units. The units of Koyna had been tested for overspeed and the devices had been set to trip at 25 per cent overspeed. The possibility of their tripping because of overspeed does not, therefore, exist. It may thus be concluded that the overspeed relays picked up because of the earthquake. On the stage II units there is another overspeed device fixed on the shaft at the governor floor. This device works on the deflection of a strip spring which comes into play when the speed exceeds a predetermined level. It is of the hand-reset type. It is interesting to note that there is no record of this having tripped at the time of the earthquake.

Selected Recommendations

The maintenance and repair works carried out on generator units were of such a nature as to bring back the machines on line within the shortest possible time even though generator shaft alignment had to be carried out. The performance of the machines after the earthquake may be said to be satisfactory, the temperature records being within the specified limits. When the alignment of the shaft was being carried out after the earthquake, it was found that this work was comparatively difficult on the stage II units because of the type of guide bearing provided, The bearings are of the shell type, as distinct from the adjustable type provided in stage I. It is, therefore, recommended that stage II generator units also be provided with a similar type of adjustable quick bearings.

The oil pressure and oil level relays in the turbine governor system had picked up at the time of the earthquake, presumably because of lack of pressure prior to the occurrence of the earthquake. This contingency should definitely be avoided, and the best course for this would be to check scrupulously the oil level and the pressure in the governor oil container to ensure that they are always kept up to the required value. As a normal procedure, it is further recommended, that in the event of tripping of the turbine unit due to an earthquake, it should invariably be ensured, before restarting the unit, that bearing clearances are in order and that conjugation between needle and deflector is perfect. All of the bypasses and pipes of the oil and water circuits to the servomotors should be in perfect condition, and the level in the oil pressure container should also be normal. If possible, the level of the turbine runner should also be checked *vis-à-vis* the position of the nozzle, before starting the units.

The latching mechanism for the counterweight of the butterfly valve, which keeps the valve in open position, was examined. In order to avoid any mal-operation of this mechanism and consequent closing of the butterfly valve, it should be ensured that the latching mechanism is properly matched.

Circuit breakers installed on future sets should not be provided with castors for the tank, as is the case in the stage I circuit breakers, The possiblity of removing the wheels from the existing circuit breakers may also be examined. It is interesting to note that more damage has been caused to stage I 3500-MVA breakers than to the stage II breakers of 7500-MVA rupturing capacity. The latter type appears to be stronger mechanically. The fault study has shown that the breakers at Koyna should be of rupturing capacity greater than 5000 MVA. The replacement of the breakers of stage I which is in any case necessary, should be done without delay.

There were a few cases of settling of the apparatus foundations, such as those of the current transformer of Bombay line 1. Calculations for all foundations should take into account the accelerations due to earthquakes and, if necessary, the base of the foundation should include strengthening by means of a suitable raft. It is possible that the damage to the circuit breaker and current transformer foundations near the cable trench may have been caused by adverse effects of vibration, due to improperly compacted ground below. In the future, no heavy structure or heavy load due to foundations of structures should be concentrated near excavations such as power cable trenches, etc., since even under ordinary monsoon conditions there is likely to be some seepage and the foundations may have a tendency to settle. The vicinity of such trenches should be properly compacted with small aggregate before the foundations of the apparatus are laid, and the foundations themselves should be strutted by suitable piling to prevent unbalanced settling.

Modifications carried out after the earthquake consisted of providing side supports for the middle tier of battery racks. It is suggested that supports be added for the top tier, at suitable intervals throughout its entire length. These side supports should be anchored rigidly at several places. With regard to the battery station inside the powerhouse, it is suggested that the racks be rigidly strutted to the walls and ceiling at suitable points. It is suggested that the height of battery racks in future installations should be kept to a minimum and that their width be increased. If possible, racks should be completely avoided and the batteries laid at ground level.

A few tube lamps had been thrown out by the earthquake. It is suggested that the fixing arrangement and holders of the tube lamps be changed to another type so that the lamps will not be thrown out because of vibration. If the present type of lamp continues to be used, some fixing clamps may be provided between the lamps and the fixtures as an additional measure of safety. As far as possible, tube lamps should be supported from the ceiling with short suspensions.

Since the present 220-kv breakers close on air failure and since these are hand-operated switches (isolators), the following protection should be added. In the event of a trip impulse to the 220-kv breaker of any unit and simultaneous air failure developing on the same, arrangements should be made to trip all of the breakers in that section of the 220-kv switchyard, including the junction breaker. Similarly, in the event of a trip impulse and simultaneous air failure on a line breaker, a trip impulse should be given by reliable and secure arrangement to all of the outgoing line breakers at the far end of the section. Simultaneously, similar trip impulses should be given to the unit breakers and the junction breaker. (In the event of air failure of the junction breaker together with a trip impulse, all of the breakers at Koyna will trip out.) The trip impulses mentioned above should cause three-phase opening and lock-out of the line breakers.

The entire protective system is dependent on the maintenance and existence of a proper communication system. A carrier system is provided. This should be always in good repair and maintenance, to provide channels for the transmission of tripping signals and essential orders. The carrier communication and the carrier protective equipment did not fail during or after the earthquake. However, in the event of loss of carrier communication, it is very essential to have some suitable and dependable means of communication on which to rely. It is therefore recommended that steps be taken to install a means of communication other than carrier, to act as a standby and be available for use in the event of loss of the carrier communication.

During the earthquake the machines tripped as a result of mal-operation of the overspeed devices. This was a very chancy matter. In the event of a similar or near similar situation unfortunately recurring, more positive means should be provided for safeguarding the station. It is therefore recommended that three separate accelerographs (each capable of sensing acceleration in all three directions) should be installed at three suitable points and connected in such a way that in the event of any severe tremor occurring beyond a predetermined value, the indications of two two such accelerographs should initiate a tripping sequence to shut down the station completely. The value at which such tripping should be initiated is tentatively recommended to be 0.35 g, subject to further detailed examination with the suppliers of the generator equipment.

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Physics of the Earth. F. D. Stacey, John Wiley and Sons, New York, 1969, xi + 324 pp. (illus.) $11.95.

The 10-year interval 1959 to 1969 has shown remarkable changes in our notions about the structure, the kinematics and the dynamics of the Earth's interior. The notions of continental drift have changed from an ephemeral vagary to a plausible and tenable hypothesis. At least one mechanism for the origin of the Earth's magnetic field has now been found. The transition between the upper and lower mantle has been found to be a succession of at least two major steps, believed to be polymorphic transitions. The notions of global plate tectonics provide an explanation for the geographic distribution of earthquake foci, and a model for the occurrence of deep focus earthquakes is now available. The advent of satellite geodesy has given definitive information about the figure of the Earth, with its consequent bearing on such notions as viscosity in the interior and with its further implications regarding convection. The observations of the free oscillations in the Chilean and Alaskan earthquakes have led to estimates of densities and seismic velocities independent of the estimates from Adams-Williamson theory operating on travel-time data.

The above truncated catalog indicates that this decade has been a truly unusual one in the history of science. I have started my decade with the year 1959 because it was in that year that Gutenberg's *The Physics of the Earth's Interior* was published. The successors to Gutenberg's book in the 10 years since it appeared have been, in the main, recapitulations of the master's.

Stacey's book is the first to provide a summary of the new discoveries and of the new models for the Earth's internal structure and constitution. The coverage is thorough and yet succinct enough for the new ideas to be conveyed in a volume as small as this one. Stacey shows himself to be an avid yet selective reader, in the best tradition of Gutenberg. Only the original contributions of the latter to the earlier volume are absent in this case.

Nevertheless, the book is an excellent exposition of modern geophysical lore. I have no hesitation in recommending it for use as a text appropriate for a class of first-year graduate students. It is the best thing that has been done of its kind and warmly deserves reading by students of geophysics, whether of the classroom variety or not. It is an important addition to any bookshelf.

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